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High Strain Rate Mechanical Properties of Glassy Polymers

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Since the early 1990s, a range of experimental data has been generated describing the response of glassy polymers to high strain rate loading *in compression*. More recently, research programs that study the combined effects of temperature and strain rate have made significant steps in providing better understanding of the physics behind the observed response, and also in modeling this response. However, limited data are available in tension, and even more limited are data describing both the compressive and tensile response of the same polymer. This paper investigates the compressive and tensile response of glassy polymers, using poly(vinyl chloride) as a representative material, across a range of stain rates from quasi-static to dynamic. The pressure dependant yield in glassy polymers will be discussed through comparison of the tensile and compressive yield stresses.

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HIGH STRAIN RATE MECHANICAL PROPERTIES OF GLASSY POLYMERS

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Abstract. Since the early 1990s, a range of experimental data has been generated describing the response of glassy polymers to high strain rate loading *in compression*. More recently, research programs that study the combined effects of temperature and strain rate have made significant steps in providing better understanding of the physics behind the observed response, and also in modeling this response. However, limited data are available in tension, and even more limited are data describing both the compressive and tensile response of the same polymer. This paper investigates the compressive and tensile response of glassy polymers, using poly(vinyl chloride) as a representative material, across a range of stain rates from quasi-static to dynamic. The pressure dependant yield in glassy polymers will be discussed through comparison of the tensile and compressive yield stresses.

Keywords: split Hopkinson pressure bar, pressure dependence, high strain rate, poly(vinyl chloride)
PACS: 62.20.-x, 81.05.Lg

INTRODUCTION

A range of experimental data has been generated describing the response of glassy polymers to high strain rate loading *in compression*. Recently, research programs that study the combined effects of temperature and strain rate have made significant steps in providing better understanding of the physics behind the observed response [1,2], and also in modeling this response [3,4]. However, limited data are available in tension, and even more limited are data describing both the compressive and tensile response of the same polymer [5-8]. In those studies that do examine tensile response, often there are large gaps in the strain rate dependence. These gaps are due to the relative difficulty of performing characterization experiments in tension, especially on polymers and especially at high rates.

Tension testing of brittle, glassy polymers, like epoxy, is even more challenging due to the low strains to failure. This brittleness can result in invalid tests due to failure outside the gauge length and susceptibility to bending. Although experimental data exists on epoxy in compression across a range of strain rates [2,9]; very little data exists in tension [5,8]. In order to achieve valid tension tests on epoxy at high strain rates, pulse shaping techniques have been developed [5,8]. Additionally, digital image correlation coupled with high speed photography has been used to measure the full field strain state in situ [8].

One very important reason for addressing this gap is that polymers exhibit pressure dependant yield, which has been measured in the past using complex loading apparatus [10-11]. However, comparison of the tensile and compressive yield stresses of individual polymers can also result in the determination of the hydrostatic pressure dependence in these materials [3,8,12].

Shock Compression of Condensed Matter - 2011
AIP Conf. Proc. 1426, 191-194 (2012); doi: 10.1063/1.3686252

In this study, poly(vinyl chloride), PVC, is used as a representative material. The compressive behavior of PVC across a range of strain rates has been experimentally studied [4,13].

EXPERIMENTAL PROCEDURE

Impact resistant PVC (Type II) in the form of 25.4 mm diameter extruded rod was machined into specimens of the appropriate dimensions. Right circular cylinders were used for all compression experiments, with the quasi-static experiments using 8 mm x 8 mm samples and the medium rate and dynamic experiments using 8 mm diameter by 3.5 mm samples. The samples for tensile experiments were based on the design by Gerlach, *et al.* [8] and were designed with a shortened gauge length and reduced radius of curvature in order to promote sample failure within the gauge length.

Dynamic Mechanical Analysis (DMA) samples (60 mm long x 12.5 mm wide x 3.2 mm thick) were tested in dual cantilever configuration in a TA Instruments Q800 at frequencies of 1, 10, and 100 Hz, displacements of 5, 10, 15, and 25 μm and a temperature range of -100 ^{o}C to 190 ^{o}C.

The quasi-static compression and tension experiments were conducted using a screw-driven Houndsfield load frame at strain rates from 10^{-3} s^{-1} to 10^{-1} s^{-1}. The strain was measured using a laser extensometer (Fiedler Optoelectronik Model P-50), which has a resolution of 0.1 μm. For the compression experiments, stripes were tracked on the compression anvils; for the tensile experiments, stripes were painted on the samples themselves.

A custom-built hydraulic load frame was used to access strain rates 1-50 s^{-1} in both tension and compression. A Linear Variable Differential Transformer (LVDT) was used to measure the displacement of the sample. Additionally, a DRS Lightening DigiStreak camera was used to image the tensile experiments. As in the quasi-static experiments, stripes were painted on the specimen, which were recorded by the camera and used to calculate strain in the gauge length.

High strain rate compression experiments were performed using a Split Hopkinson Pressure Bar (SHPB); similarly, high strain rate tension experiments were performed using a Split Hopkinson Tension Bar (SHTB). In both configurations, a gas driven projectile is used to impact either the end of the input bar in compression or a flange mounted on the end of the input bar in tension. For the SHPB system, the input and output bars are made of 6061-T6 aluminum. In the SHTB system, the input bar is Ti6Al4V and the output bar is phosphor bronze. A stress wave (compressive or tensile) then travels through the input bar until it reaches the sample. At the sample, part of the wave is reflected and part is transmitted. A pulse shaper, in the form of a preloading bar, is used on the SHTB system in order to increase the rise time of the input wave and therefore smooth the wave, in particular removing a stress peak, which often occurs [8].

The stress waves are measured using strain gauges mounted on the bars. The SHPB system uses two sets of strain gauges mounted mid-way along the length of the input and output bars. The data are acquired and analyzed as described in [14]. It is valuable to ensure that the sample is in equilibrium [15]; this was done in all experiments. The SHTP system uses three sets of strain gauges in order to record the stress waves – two on the input bar and one on the output bar. The use of three gauges allows for longer input pulses while using shorter input and output bars. The gauge signals are used to calculate the force at and velocity of the two specimen-bar interfaces using and analysis in [16]. These are, in turn, used to derive the stress and strain in the specimen. Additionally, photographs were taken of the deforming sample in order to provide a further measure of strain. A Specialised Imaging SIMX16 high speed camera was used to take 16 pictures through the duration of the loading, and an edge detection algorithm was then used to track the position of stripes painted on the specimen surface.

RESULTS AND DISCUSSION

The dynamic mechanical analysis of PVC, Figure 1, showed that the α, or glass, transition, varies from 79.5 ^{o}C at 1 Hz to 83.7 ^{o}C at 100 Hz. The lower temperature β phase transition, attributed to restrictions in secondary chain motions [3], moves from -44 ^{o}C at 1 Hz to -30.8 ^{o}C at 100 Hz. The β transition changes more than the glass transition over the same frequency range due

to the lower activation energy for the β transition.

The temperature of the phase transition as a function of *ln* ($\dot{\varepsilon}$) is plotted in Figure 2. The strain rate is determined from the test frequency, displacement, and gauge length [3]. Extrapolation of the β phase transition to room temperature results in a strain rate of ~7000 s^{-1}.

The compressive and tensile response of PVC as a function of strain rate is shown in Figure 3. The stress increases with strain rate in both cases. In both sets of experiments, the stress-strain response is typical for a glassy polymer, with an initial elastic region followed by a non-linear elastic region and yield, then strain softening followed by strain hardening. At higher strain rates (> 0.06 s^{-1}), the strain hardening is masked by thermal softening due to the transition between isothermal and adiabatic test conditions [4].

There are oscillations in the high strain rate tensile experiments, which are believed to be an experimental artifact. The real stress-strain curve is believed to be an average line fitted through the oscillations. The regular noise on this signal is due to the camera recording a picture at set intervals. These data illustrate the difficulties inherent in performing high strain rate tensile experiments on polymers, and work is ongoing to improve the quality of data obtained.

The peak stress at yield for both the tensile and compression experiments is plotted in Figure 4. For many glassy polymers, the beta phase transition results in increased yield strength under high strain rate loading [2-3]. For PVC, the DMA results predict this transition at ~7000 s^{-1}. The

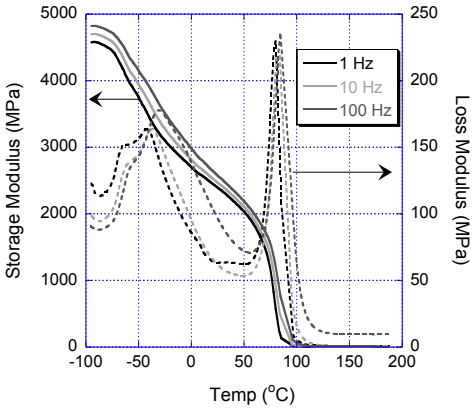

Figure 1. Dynamic mechanical analysis of PVC.

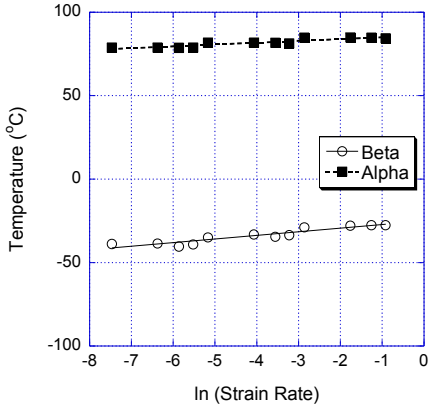

Figure 2. Shift in α and β transitions as a function of $\dot{\varepsilon}$.

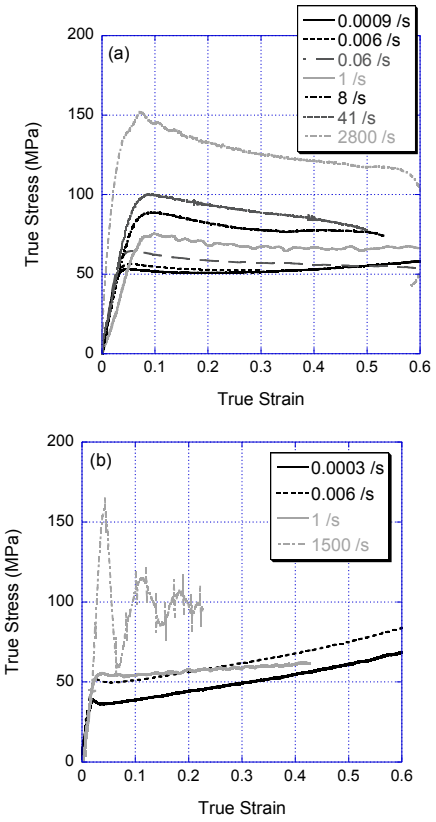

Figure 3. (a) Compressive and (b) tensile response of PVC as a function of strain rate.

yield strength as a function of strain rate is approximately linear, at perhaps other than the highest strain rate compression experiments.

The compressive yield is consistently above the tensile yield. The ratio of the yield stress in

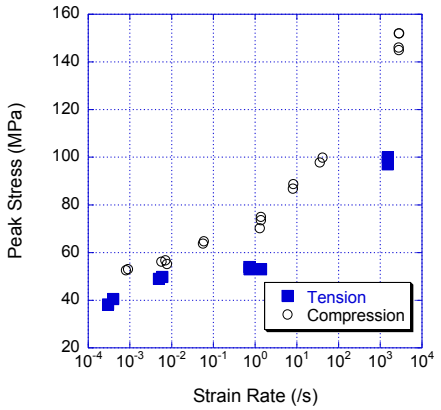

Figure 4. Peak stress versus strain rate for PVC.

compression versus tension at a given temperature and strain rate is a constant:

$$\frac{|\sigma_c|}{\sigma_t} = \frac{\sqrt{2}+\mu}{\sqrt{2}-\mu} \quad (1)$$

where σ_c is the compressive yield stress, σ_t is the tensile yield strength and μ is a constant:

$$\tau_0 + \mu p = constant \quad (2)$$

where τ_0 is the octahedral yield stress and p is the hydrostatic pressure [12]. For the data in this study, μ is ~0.22, which is in good agreement with published pressure dependant yield data [17]. From Eq. 1, the relationship between tensile and compressive yield stress should be constant when a single simply activated flow process is driving the behavior of the polymer [12]. For PVC, in this temperature and strain rate regime, only the α process is active, as indicated by the β transition strain rate extrapolating to ~7000 s^{-1}.

CONCLUSIONS

Poly(vinyl chloride), PVC, is experimentally studied in tension and compression varying strain rate. DMA indicates the presence of two phase transitions in the polymer. The α, or glass, transition, varies from 79.5 ^oC at 1 Hz to 83.7 ^oC at 100 Hz. The lower temperature, β, phase transition, attributed to restrictions in secondary chain motions, moves from -44 ^oC at 1 Hz to -30.8 ^oC at 100 Hz. The β transition strain rate extrapolates to room temperature at ~7000 s^{-1}.

The compressive and tensile stress-strain curves for PVC across a range of strain rates are typical for glassy polymers, and the yield strength increases with strain rate. The compressive yield stress is consistently higher than the tensile yield stress and both are linearly dependant on strain rate within the regime tested. The relationship between the compressive and tensile yield stress will be linear when a single simply activated flow process is driving the behavior of the polymer, which is in agreement with the extrapolation of the β transition strain rate from DMA data.

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REFERENCES

1. Siviour, C.R., Walley, S.M., Proud, W.G. and Field, J.E., *Polymer*, **46**, 12546-12555 (2005).
2. Jordan, J.L., Foley, J.R., and Siviour, C.R., *Mech. Time-Depend. Mater*, **12**, p. 249-272 (2008).
3. Mulliken, A.D., and Boyce, M.C., *Int J Solids Struct.*, **43**, 1331-1356 (2006).
4. Mulliken, A.D., Soong, S.Y., Boyce, M.C. and Cohen, R.E, *J Phys IV Fr*, **134**, 217-223 (2006).
5. Chen, W., Lu, F. and Cheng, M. *Polym Test.*, **21**, 113-121 (2002).
6. Sarva, S., Mulliken, A.D. and Boyce, M.C., *J Phys IV France*, **134**, 95-101 (2006).
7. Roland, C.M., Twigg, J.N., Vu, Y. and Mott, P.H. *Polymer*, **48**, 574-578 (2007).
8. Gerlach, R., Siviour, C.R., Petrinic, N. and Wiegand, J., *Polymer*, **49** [11], 2728-2737 (2008).
9. Lu, H., Tan, G., and Chen, W., *Mech Time-Depend Mater*, **5**, 119-130 (2001).
10. Mears, D.R., Pae, K.D., and Sauer, J.A., *J. Appl. Phys.*, **40** [11], 4229-4237 (1969).
11. Sauer, J.A., Mears, D.R., and Pae, K.D., *Eur Polym J*, **6**, 1015-1032 (1970).
12. Bauwens-Crowet, C., Bauwens, J.-C. and Homes, G., *J Mater Sci*, **7**, 176-183 (1972).
13. Bauwens, J.-C., Bauwens-Crowet, C. and Homes, G., *J Polym Sci*, **7**, 1745-1754 (1969).
14. Jordan, J.L., Siviour, C.R., Foley, J.R., and Brown, E.N., *Polymer*, **48** [14], 4184-4195 (2007).
15. Gray, G.T., ASM Handbook Vol 8, 462-476 (2000).
16. Harding, J. and Welsh, L.M., *J Mater Sci,* **18**, 1810-1826 (1983).
17. Pae, K.D. and Bhateja, S.K., *Polym Rev,* **13**, 1-75 (1975).

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